

The University of Chicago

GEOLOGY OF THE NORTHEASTERN
PART OF THE IDAHO BATHOLITH
AND ADJACENT REGION
IN MONTANA

A PART OF A DISSERTATION SUBMITTED
TO THE FACULTY OF THE DIVISION OF THE
PHYSICAL SCIENCES IN CANDIDACY FOR
THE DEGREE OF DOCTOR OF PHILOSOPHY

DEPARTMENT OF GEOLOGY AND PALEONTOLOGY

1934

By

CLAUDE MAURICE LANGTON

Private Edition, Distributed by
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CLAUDE M. LANGTON
University of Chicago

ABSTRACT

The region is composed mainly of sediments of the Belt series and of gneisses and schists in the immediate vicinity of the Idaho batholith. The structures become more complex as one approaches the batholith, and evidence is given for two periods of folding and faulting of which the later deformation occurred near the time of the batholithic emplacement. Important is the fact that a series of thrust faults parallels the northeastern portion of the batholith; it is believed that these thrusts have been produced by batholithic forces pushing outward. Assimilation seems to have been of little importance in the emplacement of the batholith, but stoping has played an important part.

The Bitterroot Valley, previously considered due to normal faulting, is found to have experienced a complex history consisting of thrust faulting, intrusions, underthrusting, and later normal faulting.

INTRODUCTION

The area described in this paper lies within Missoula, Ravalli, and Granite counties, Montana. It extends southward from the city of Missoula nearly to Hamilton, and from the Idaho-Montana boundary eastward to Rock Creek, covering, in all, about 1,300 square miles. The area is bisected by the Bitterroot River into eastern and western divisions, the former comprising the Sapphire Range; the latter, the Bitterroot and Graves Creek ranges (Fig. 1).

Work was commenced in the summer of 1932 in the northern part of the area where the rocks show the least complexity. After the simpler structural patterns had been interpreted, the work progressed southward into the more complexly deformed area which is nearer the northeastern margin of the Idaho batholith. In all, the writer spent 130 days of actual field work, mapping the structures. Previous to this, Dr. C. H. Clapp of the University of Montana, had mapped the area in a reconnaissance manner, but his maps have not been published, although they have been freely consulted by the writer.

¹ Published with permission of the Montana State Bureau of Mines and Geology

Much credit is given to Dr. Clapp, for use of his maps; and since he was in charge of the field work and was with the writer during nearly one-third of the time spent in the field, many interpretations

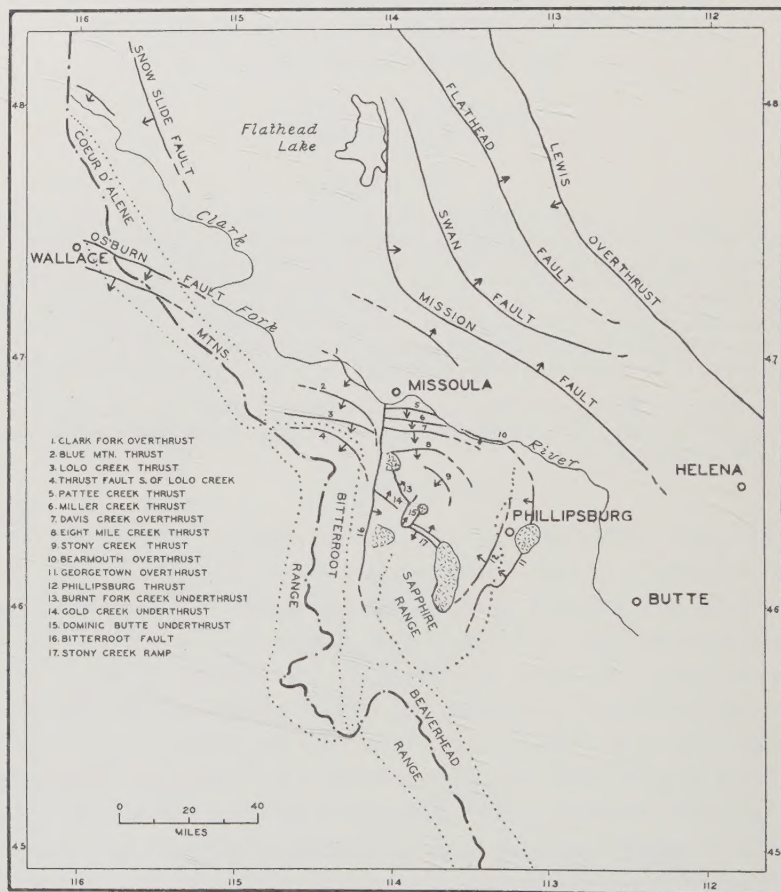


FIG. 1.—Index map, showing major fault patterns of Western Montana

of the structures in the complex areas are primarily his own. Dr. R. T. Chamberlin offered many valuable suggestions during the preparation of the manuscript, and to him the writer is deeply indebted. Also to Professor A. Johannsen thanks are given for his aid in the examination of the rock sections.

PHYSIOGRAPHY

The physiography of the Bitterroot Range has been well described by Dr. W. Lindgren.² Only the characteristics germane to the structural problems of the region are given here, of which the major feature is the uniform dip of the eastern front of the range to the Bitterroot Valley. This bold front is a persistent and regular one, and it has an average dip of about 25° . It extends the full length of the Bitterroot Range and comprises a zone composed of both sedimentary and granite gneisses, which will be described in detail later. Another feature of the Bitterroot Range is the gradual increase in altitude of the summit peaks from north to south, showing a greater elevation of the southern part of the region. The ruggedness of the Bitterroot Range, because of intense glaciation on the underlying rocks of gneisses and schists, is probably not exceeded by any other ranges within the Rocky Mountains (Fig. 2).

The physiographic development of the Sapphire and Graves Creek ranges is in strong contrast to that of the Bitterroot Range; but, like the Bitterroot Range, the Sapphire Mountains have been uplifted considerably higher in their south extension than in the north. In general the range resembles a broad, dissected plateau. The major streams within the Sapphire Range mostly head southward and are in part subsequent and in part superimposed.

The Bitterroot River is the major stream within the area. Because of its significant relation to the geologic structures of the region, it is described most fully in this paper. The valley proper is about 65 miles long and nearly 9 miles in width, with a nearly straight north-south trend. On the west, the Bitterroot Range rises with its remarkably even slope and deeply incised canyons; on the east, with gentler slope and far less pronounced outlines, are the foothills of the Sapphire Range. Roughly outlined, the shape of the valley is that of a broad-bottomed, unsymmetrical boat, narrowing at both ends. Few, if any, outcrops occur directly within the valley except from the mouth of Lolo Creek northward. Within this short distance, the valley loses its basin-like shape and the river is superimposed upon faulted rocks of the Belt series. The depth of the river

² W. Lindgren, "A Geological Reconnaissance across the Bitterroot Range and Clearwater Mountains in Montana and Idaho," *U.S. Geol. Surv. Prof. Paper 27* (1904).



FIG. 2.—Photograph taken looking south up the South Fork of Lolo Creek, Bitterroot Range. Heavenly Twins in the central background; elevation, 9,329 feet.

gravels, or lake deposits, as shown by a well drilled near Corvallis, is over 1,100 feet; and the total depth of the basin may be twice this amount. The valley is probably a downwarp with the western side a complexly sheared fault zone. Perhaps with the filling of the basin in Tertiary time, with greater uplift in the southern part of the basin, and damming of the Snake River with lava flows, a spillway was developed on the north where now exists the mouth of the stream, and hence the reason for the narrowing of the river valley near the town of Lolo and northward.

STRATIGRAPHY

The predominant sedimentary rocks of the area belong to the Belt series. Probably nowhere else in Montana are so many of the Belt formations represented in an area of equal size as in the northern part of the Sapphire Range. The sediments of this area may represent the maximum thickness of the Belt series and probably reach well over 50,000 feet.³ The formations vary from 2,000 to 8,000 feet in thickness and are largely composed of argillites, sandstones, and quartzites. Each formation usually contains some beds lithologically similar to beds in other formations of the same series so that it is often necessary to ascertain the relations of the formation being mapped to the formations above or below before its place in the stratigraphic column can be definitely fixed. The age of the formations becomes progressively older from the Clark Fork River southward, the reasons for this being threefold: (1) thrust faulting from the south, (2) synclinal nature of a narrow lineament to be discussed later, and (3) a relatively greater uplift of the southern part of the range than of the northern part. However, a repetition of younger formations occurs in the extreme southern portion of the area mapped. This is due to underthrust faulting. Because of the structural complexity of the area, no attempts were made by the writer to measure the sections. However, the type sections⁴ of the Hellgate and Miller Peak formations occur in the extreme northern part of the Sapphire Range.

³ C. H. Clapp, "Geology of a Portion of the Rocky Mountains of Northwestern Montana," *Mont. Bur. of Mines and Geol., Mem. 4* (1932), p. 18.

⁴ C. H. Clapp and C. F. Deiss, "Correlation of the Algonkian Formations in Montana," *Geol. Soc. Amer. Bull.* 42 (1931), pp. 673-96.

GEOLOGY OF NORTHEASTERN PART OF THE IDAHO BATHOLITH AND ADJACENT REGION IN MONTANA

1 2 3 4 5 6 7 8 9 10 MILES

1934

Geology by C.M. Langston, C.H. Clapp
in charge, 1932-1934.
Base from U.S.G. Topographic maps
of the Bonner, Missoula, Hamilton,
and Sapphire quadrangles.

Bonner

MISSOULA

CLARK FORK RIVER

DEEP CREEK

NORTHERN PACIFIC RAILROAD

114° 15'

114° 30'

46° 30'

46° 15'

46° 00'

45° 45'

45° 30'

45° 15'

45° 00'

44° 45'

44° 30'

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Since Emmons and Calkins⁵ have described in detail the Lower Belt series in the Philipsburg area, which lies on the east adjacent to the Sapphire Range, and Clapp and Deiss⁶ have recently described the "Missoula group" or Upper Belt series, only a tabular description is given here (Table I).

A few square miles of Paleozoic limestone lie along the Clark Fork River in the extreme northwest portion of the area. A definite age cannot be assigned to the limestone, as no fossils were found. It is here tentatively correlated with the Hasmark formation of Cambrian age, since, lithologically, it compares well with that formation described by Calkins in the Philipsburg district. However, a very petroliferous odor is characteristic of the limestone, which is not true of the Hasmark formation but is more typical of the Jefferson limestone of Devonian age. On the other hand, the Jefferson limestone, in contrast to these limestones, carries an abundant fauna. In view of the fact that the contact of the Upper Belt rocks with the limestone is a faulted one, we must await the finding of fossils before any permanent correlation is made.

No other sediments except slightly consolidated Tertiary lake beds, late Pleistocene deposits, and Recent gravels occur within the area. These are confined to the major stream valleys and were not studied in detail; they are, therefore, not differentiated on the map. In fact, no exposures carrying fossils of definitely Tertiary age were noted, but the indurated gravels covering the lake benches on either side of the Bitterroot Valley are retained on the map as Tertiary. Undoubtedly these deposits of gravels and subangular boulders represent, in part, Pleistocene fill in "Lake Missoula."⁷ These benches or terraces are readily observed along the major streams up to 4,300 feet in elevation, which represents the height which Lake Missoula once attained. The lower benches, however, probably consist of Tertiary lake beds now covered by the later gravels, as Lindgren⁸ has described a deposit of lignite coal of Tertiary age near the

⁵ W. H. Emmons and F. C. Calkins, "Geology and Ore Deposits of the Philipsburg Quadrangle, Montana," *U.S. Geol. Surv. Prof. Paper* 78 (1913).

⁶ Clapp and Deiss, *op. cit.*, pp. 673-96.

⁷ J. T. Pardee, "The Glacial Lake Missoula," *Jour. Geol.*, Vol. XVIII (1910), pp. 376-86.

⁸ Lindgren, *op. cit.*, pp. 111-13.

TABLE I
SEDIMENTARY ROCKS

Geologic Age			Formation	Thickness	Character
CENOZOIC	Quaternary	Recent	Alluvium		Silt, sand, and gravel that form flats along the streams are locally gold-bearing.
		Pleistocene	Terrace gravels		Moderately thick deposits covering Lake Missoula terraces or benchlands along Clark Fork and Bitterroot valleys extending up to an elevation of 4,300 feet. Few exposures of varved clays along Clark Fork River. Glacial drift but slightly weathered; probably re-worked lateral and terminal moraines.
			Lake Missoula beds		
			Glacial drift		
	Tertiary	Oligocene-Miocene and Pliocene	Lake beds		Massive silts underlying bench gravels on east side of Bitterroot Valley. Generally concealed by superficial material, and seen only in road cuts. In southern end of the Bitterroot Valley some coal seams outcrop. In most valleys of western Montana, volcanic ash is common.
PALEOZOIC	Cambrian		Hasmark? formation	1,000 ± ft.	Dolomitic, massive-bedded, grayish weathering limestone, with a characteristic petroliferous odor, lying disconformably upon whiter, siliceous limestone, interbedded with brownish cherty laminae with some shale. Unfossiliferous. May represent the upper part of the Silver Hill, Hasmark, and lower part of the Red Lion formations.

Faulted Contact

ALCONKIAN	Missoula Group*	Garnet range formation	6,500 ± ft.	Upper 3,000 feet consist of brownish and greenish micaceous, thin-bedded argillitic quartzite overlying 300 feet of pure coarse-grained purple quartzite. Beneath this purple quartzite are 1,600 feet of brown, green, and gray quartzitic sandstone, overlain by another 1,600 feet of brown, green, and gray micaceous quartzites and argillites. Only the upper part is exposed in the mapped area.
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* Descriptions of Missoula Group taken from Clapp and Deiss; Lower Belt descriptions, from Calkins, Philipsburg area.

TABLE I—*Continued*

Geologic Age		Formation	Thickness	Character
ALGONKIAN— <i>Continued</i>	Missoula Group— <i>Continued</i>	McNamara	3,000 ± ft.	Upper 1,800 feet consist mostly of alternating beds of red, gray, and greenish, fine-grained, mud-cracked argillites and sandstones. Lower part comprises pink and white massive quartzite interbedded with maroon-colored sandy argillites.
		Hellgate	2,200 ± ft.	Massive red to pinkish gray quartzite. Cross bedded, ripple marked, and interbedded with thin beds of red argillite.
		Miller Peak	2,900 ± ft.	Massive to thin-bedded, purple and gray sandstones and argillites. Lower part comprises calcareous buff weathering thin-bedded mud-cracked argillites.
	Lower Belt	Helena	4,000 ± ft.	Thin-bedded, argillaceous and sideritic limestone with parts dolomitic. Beds weather to a buff or cream color and often show "molar tooth" structure.
		Spokane		Upper part massive to thin-bedded lavender-colored quartzites. Lower 2,000 ft. consist of greenish-gray and in part calcareous argillites showing ripple marks.
		Newland	4,000 ± ft.	Impure argillitic, dolomitic, and sideritic limestones, with some blue, thin-bedded, ripple-marked argillites.
		Grinnell	7,000 ± ft.	Upper portion consists of bluish-gray, fine-grained thin-bedded argillites grading downward into more massive-bedded gray quartzitic argillites, commonly ripple-marked and with layers of reddish gray quartzites.
		Appekunny	6,000 + ft.	Predominantly massive, bluish-gray and light gray argillitic quartzites, grading downward into very massive gray quartzites.
		Prichard	5,000 ± ft.	Predominantly brownish sandstones often containing feldspar, highly metamorphosed to biotite-muscovite schist in the area mapped. The formation is intruded by the older gneiss on Lolo Mountain.

south end of the valley on the Nez Perce Fork; also along the other major valleys of western Montana remains of both Tertiary vertebrates and invertebrates are widely known.

IGNEOUS ROCKS

GENERAL

The igneous rocks within the area are numerous; and the region is literally spotted with small bosses, dikes, and sills. They are similar in composition, and their mineral components show a close relationship between the hypabyssals and the plutonites, although only about thirty-five different specimens have been studied by the writer. A few of the different types are briefly described here. In general the majority of the hypabyssal rocks are slightly soda rich, as shown by blue hornblende (riebeckite) or albite or oligoclase feldspar.

IDAHO BATHOLITH

The Idaho batholith, which is exposed over an area of approximately 16,000 square miles,⁹ is one of the greater batholiths of North America. But what is thought to represent the true massive phase of the batholith comprises an area of only a few square miles in the extreme southwestern corner of the region. Practically the entire area of nearly 200 square miles mapped in the Bitterroot Range is composed of schists, gneisses, and later unaltered injections which are related to the batholith. Megascopically the massive phase is a normal granular rock, made often roughly porphyritic by the development of large orthoclase and oligoclase crystals up to an inch or more in diameter. The color is prevailingly a light gray, but the slightly weathered outcrops assume a yellowish-gray color. Biotite is always present, and muscovite is common. Quartz is often abundant in medium-sized grains, but the amount varies considerably; while the feldspars are represented by both orthoclase¹⁰ and oligoclase, the

⁹ C. P. Ross, "Mesozoic and Tertiary Granitic Rocks in Idaho," *Jour. Geol.*, Vol. XXXVI (1928), p. 676.

¹⁰ A. L. Anderson and A. C. Rossor, "Composition of Part of the Idaho Batholith, Boise Co., Idaho," *Amer. Jour. Sci.*, 5th ser., Vol. XXVII (1934), pp. 287-94. Described the core of the batholith as composed of microcline instead of orthoclase. No microcline has been observed in the sections studied by the writer, and the percentage of orthoclase is somewhat less than the amount of microcline as calculated by them.

latter in large quantity. Under the microscope perthite is frequently seen; and in some cases the oligoclase is complexly twinned, giving nearly a microcline plaid effect. The rock contains far too much oligoclase to be classed as a normal granite but varies from a quartz-monzonite (adamellite) or grano-diorite to a true tonalite. Few accessory minerals except zircon and apatite were noted, though titanite occurs abundantly in the hornblende-rich segregations of



FIG. 4.—“Younger gneiss.” Cross Nicols $\times 38$

the same granite. All the specimens studied show some effects of pressure, as indicated by the undulating extinction of the quartz. The typical specimen contains the following essentials: biotite, 10 per cent; quartz, 33 per cent; oligoclase, 41 per cent; and orthoclase, 16 per cent.

Younger gneiss.—Surrounding the more massive granite described above, is a border phase of schlieren gneiss, which in turn is bordered on

the east by what is believed to be a much older gneiss. The younger gneiss grades outward with increasing schistosity from the massive granite. The zone of schlieren gneiss extends for a distance of over 12 miles northward from the northeast margin of the batholith and forms the major part of the Bitterroot Range from St. Joseph Peak northward beyond Lolo Peak. On the east side of the batholith this gneiss continues southward with an average width of nearly 5 miles, but narrows rapidly southward until, between Sweathouse and Bear Creek, it is less than a mile in width. This zone is highly intruded by numerous leucocratic stocks and tonalite-aplite dikes, as well as pegmatites and hornblende-rich dikes. Some of these intrusions are sheared and foliated. The outer part of the zone con-

tains numerous xenoliths and remnants of roof pendants, the latter being most commonly found on the higher ridges. The strike of the gneiss generally parallels the border of the massive granite, but the dip varies considerably, giving an asymmetrical anticlinal-like structure. The west limb is the steeper (50° – 80°), while the eastern flank dips toward the valley at a lower angle. The anticlinal structure trends slightly west of north, and near its axis the schlieren gneiss is less prominently developed and is nearly horizontal. The massive phase of the batholith lies to the west of the structure, and the western limb apparently dips beneath it. The cause of this structure may be a large intrusion which is not exposed at the surface. On the extreme north, the gneiss is more schistose than on the east. In places the gneiss is decidedly crinkled perpendicular to the normal cleavage planes, and

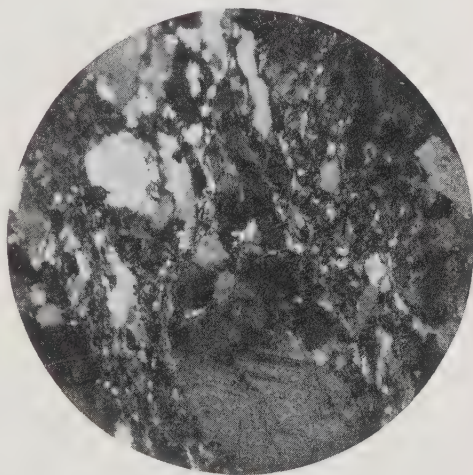


FIG. 5.—“Older gneiss.” Granulated Cross Nicols $\times 36$.

biotite and muscovite make up a large portion of the rock. It is not impossible that this crinkled gneiss may be older and may belong either to the outer zone of gneiss described below or may have been derived in part from the sandy argillitic Prichard formation.

Thin sections of the schlieren gneiss show little orthoclase but a high percentage of muscovite. The rock is, however, the metamorphosed equivalent of the massive granite. An average of five specimens gives 9 per cent biotite, 17 per cent muscovite, 23 per cent oligoclase, 47 per cent quartz, and only 3 per cent orthoclase. Of the few accessory minerals garnet appears to be in larger amounts than in the massive granite.

Older gneiss.—A gneissic zone, which is thought to be older than

the schlieren gneiss just described, extends along the eastern front from Carlton Creek southward for over 50 miles. This zone averages less than 2 miles in width from Carlton Creek to Sweathouse Creek but widens to over 3 miles along Bear Creek. The gneiss dips toward the valley at an angle of 15° – 30° , which is nearly parallel with the slope of the mountain front. This older gneiss may also curve westward in the northern part of the range; but, because of the strong schistosity, it could not be differentiated there from the younger gneiss. The contact of the two zones is fairly sharp and readily detected in some places, but in others there may be a gradational zone. The writer cannot do better than quote Lindgren's¹¹ description of this gneiss.

The normal gneiss from Mill Creek,¹² two miles above the mouth of the canyon is a plainly schistose rock with large orthoclase crystals pressed into partly lenticular shape. Biotite and a little muscovite lie in flat aggregates between streaks of pressed feldspar and quartz. There is much cataclastic action and formation of new allotrimorphic aggregates along wavy lines, which indicate schistosity. Large feldspar and quartz grains, when crossed by these lines, are greatly crushed. On the whole, however, the rock has similarity to the normal Bitterroot granite.

Stronger crushing action near the mouth of the canyons simply results in emphasizing the characteristics already referred to. The sinuous lines along which most active recrystallizing movement is in progress multiply, and at last the whole rock is transformed into a fine-grained aggregate traversed by wavy streaks of finely distributed biotite and a little muscovite, and in this mass lie as pseudophenocrysts the irregular, more frequently lenticular remains of larger grains. These are often cut by parallel cracks which dip about 70° east, and which are sometimes opened and filled by secondary quartz, suggesting a stretching movement.

Because of these numerous slipping planes paralleling the essentially regular slope of the east front of the range, Lindgren postulated the Bitterroot fault, which will be discussed later.

Thin sections of this gneiss have been studied, but the writer fails to agree with Lindgren that the rock is but the metamorphosed equivalent of the younger gneiss or the massive granite. It seems

¹¹ Lindgren, *op. cit.*, p. 37.

¹² The Mill Creek referred to by Lindgren is not the Mill Creek shown on this map, but occurs farther south and is also a western tributary of the Bitterroot.

more likely that this gneiss is the equivalent of an older true granite and not the quartz monzonite or granodiorite from which the schlieren gneiss developed. The average percentages of the essential minerals are as follows: orthoclase, 45 per cent; quartz, 34 per cent; muscovite, 3 per cent; biotite, 5 per cent; and oligoclase only 13 per cent. It is noteworthy that there is but slight development of muscovite and biotite, and that orthoclase is three times as abundant as oligoclase. It seems certain that the relative amounts of the potash feldspar and oligoclase of the two gneisses indicate a difference in origin. The former, or younger, gneiss has been developed from the true quartz-monzonite or granodiorite; whereas the latter is probably older and derived from a true granite which may be much older.

Xenoliths.—Only a few of the larger xenoliths are shown on the map, and their boundaries are tentatively drawn. They consist of quartzites, sandstones, greenish metamorphosed limestones, and a few blocks of the older gneiss. The xenoliths are most numerous near the margin of the younger gneiss, show little or no rounding, and are nearly always ptymatically folded with the lit-par-lit injections which probably make up 50 per cent of the blocks. Some of the xenoliths conform in strike and dip with the gneiss, but more commonly they are irregularly arranged.

Roof pendants.—Roof pendants consisting of quartzites and brownish sandstones occur on the crests of the higher ridges and in the mountain peaks. Their presence is easily detected at some distance by the reddish brown weathering of the sandstones. Like the xenoliths, the pendants show close folding with lit-par-lit injections which locally form a large part of the rock. These injections vary considerably in thickness within short distances and form lenses or even nearly spherical bodies (Fig. 6). In some places the bedding or planes of schistosity bend around the injected masses; whereas in other places the injections transect the cleavage planes. Lindgren¹³ found no sediments remaining with the feldspar and mica schist in the mechanically weathered material on the ridges; and therefore suggested that these upper ridges, as on St. Mary's Peak, represent

¹³ Lindgren, *op. cit.*, p. 37.

remnants of an older schist probably Archean in age. More detailed work, however, shows that not only does some sandstone occur on the tops of the ridges but also that sandstone xenoliths occur below these pendants, and the possibility of an Archean age of the gneiss is eliminated.

A most interesting roof pendant about 2 miles in length occurs on the spur north of the mouth of Mill Creek. It is composed of three limestone beds which are repeatedly faulted against bluish

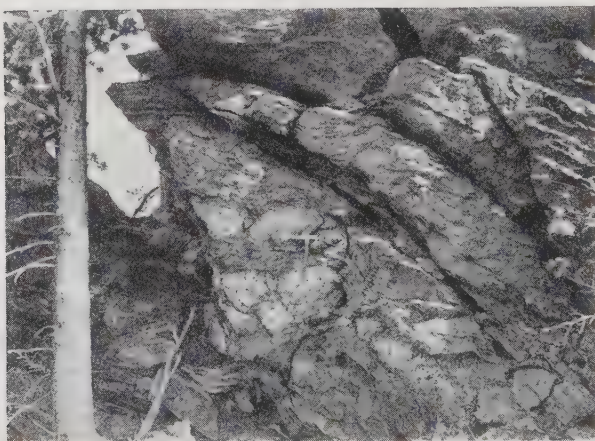


FIG. 6.—Spherical “eyes” of granite in a roof pendant on ridge north of Carlton Creek.

quartzitic argillites. These beds undoubtedly represent the Grinnell or Appekunny and Newland formations. The strike of the bedding and of the faults nearly parallels the Bitterroot Valley. Both the limestone and quartzitic argillites also show slickensides with a dip similar to that of the gneiss. The pendant extends across the contact of both the older and younger gneiss, indicating that the former, as well as the latter, is post-Beltian in age.

Assimilation.—Evidence of assimilation in either the xenoliths or border sediments is meager. The xenoliths are exceedingly angular; and even small inclusions of quartzite, highly recrystallized, show no evidences of solution. In connection with lit-par-lit injections into schists or gneisses, assimilation is a recognized phase of the process of granitization. But within the lit-par-lit zones of both

the roof pendants and within the older gneiss, there is no apparent hybridism. Sillimanite was, however, found to the extent of 5 per cent in one specimen near the contact of a xenolith. On the whole, assimilation appears to have played a small part.

Stoping.—Stopping apparently has played a more important rôle in the emplacement of the batholith than has assimilation. The northern part of the range, from Carlton Lakes throughout the area mapped as Prichard, is truly a shatter zone composed of Prichard sedimentary rocks riven with many apophyses forming a network of dikes. Many of these blocks have been completely surrounded by magma and have settled within it to at least 2,000 feet below the roof, so as to be now exposed in the bottoms of the cirques as well as along the deeply incised gulches in Carlton, Sweeney, and other creeks. Nevertheless, the angularity of the blocks is as apparent in these xenoliths as in the blocks which appear to have floated on top of the magma. Although the northern contact of the intrusive gneiss with the sediments appears on the map to be fairly smooth, detailed mapping would show it to be more irregular.

STOCKS

The Willow Creek stock intrudes the Newland limestone near the southern boundary of the area east of Corvallis. Only the northern margin of the stock was traced, but it probably has an exposed area of over 15 square miles and is elongated in an east-west direction. Three specimens examined show that the rock varies considerably in the quartz-feldspar ratio but belongs to the leuco-quartz monzonite family. The rock averages about 35 per cent quartz, 30 per cent orthoclase, 32 per cent oligoclase, with less than 5 per cent biotite. Muscovite, apatite, and zircon are sparingly persistent.

The Boulder Basin stock comprises an area of over 17 square miles between Rock Creek and the crest of the Sapphire Range. Its outline is nearly square. In places the granite is somewhat sheared; but the Dominic Butte underthrust could not be traced in it, suggesting that the granite is perhaps younger than the underthrust. It is similar in composition to the Willow Creek stock.

The Ambrose Creek stock, which also is similar in composition to the other two, has an exposed area of about 25 square miles; but

the general trend of the exposed contact would indicate that over half of the stock is covered by gravels. The eastern margin of the mass is interesting because of its very regular contact with the Appekunny quartzites. Time was not available, nor exposures of the rocks adequate, to apply Cloos's methods on the flow structure. Some evidence of shoving, however, is manifested by (1) definite underthrusting of the Appekunny quartzites on the ridge near the northeast contact, and indirectly perhaps by (2) absence of doming of the country rock, as is conclusively shown by the dip of the sediments beneath the stock on the south and east, and (3) lack of evidence for stoping, such as xenoliths, blocky contacts, and lit-par-lit injections.

HYPABYSSALS

The dikes, sill-like injections, and small bosses within the area are very numerous. Few of these smaller injections can be traced for any great distance, but their relations to the later deformation of the region are clear. The dikes, which vary in type from monzo-gabbros through tonalites and quartz monzonites, usually follow the strike of the faults. In fact, they are so numerous along the faults that one always looks for faulting if a dike is found, or looks for a dike to give further evidence of a supposed fault. Most of the dikes are usually somewhat sheared and hydrothermally altered, but some are fresh and appear to be slightly later than the faulting. Evidence that faulting and injection went on simultaneously was seen near the northern contact of the Boulder Basin stock. Here an injection was noted intruding along a fault in quartzite with a later fault offsetting the earlier one and the dike.

A small area of andesite occurs along the Clark Fork River north of Schwartz Creek. No flow structure was noted, and the contact is obscured by drift. The Andesite may be a dike intruding along the Pattee Creek fault or it may be a remnant of a flow, as Pardee¹⁴ has reported dacite extrusives a few miles to the east.

AGE OF THE IDAHO BATHOLITH

Ross¹⁵ has summarized the literature concerning the intrusive bodies in Idaho and southwestern Montana but has left the age of

¹⁴ Pardee, *op. cit.*, p. 169 (also map).

¹⁵ Ross, *op. cit.*, pp. 673-93.

the Idaho batholith still an open question. Little information on the age of the major batholith can be obtained from the area studied. That the major batholith is composite, comprising a group of batholiths and smaller bodies differing somewhat in age, is evident. It is very likely that the northern third or more of the Bitterroot Range consists of intrusions that are later than the schlieren gneiss, which is thought to be of the same age as the Idaho batholith. If we assume that the minor structures of this area, to be discussed later, are closely related to the batholith, it follows that the batholith is not only Cretaceous or Eocene in age but that its emplacement followed the major or north-south trending structures which developed in the earlier part of the Laramide deformation. On the other hand, it is not at all impossible that the batholith may in part be Jurassic, as some have supposed, and that only the eastern or northeastern portions are of later age. This would be in harmony with Lindgren's¹⁶ suggestion of a progressive eastward migration of the later intrusions.

STRUCTURE

GENERAL

In western Montana the Rocky Mountains have been divided on a structural basis into a northern area of linear ranges trending in a general N. 30° W. direction and a southern area in which the mountain ranges are diversely arranged.¹⁷ The northern linear ranges

are in strong contrast to that of the southern ranges of the state, because their structure is simpler, and because they are composed almost entirely of sedimentary rocks; although igneous rocks do form conspicuous sills and in a few places small granitic stocks. To the south, however, igneous rocks, in batholithic, injected, and volcanic masses become the dominant rocks of many of the mountain clusters and diversely arranged linear ranges.

The zone separating the two geologic divisions of western Montana is narrow and fairly well defined. It extends slightly southeast from the Cœur d'Alene district of northern Idaho to Missoula and thence almost due east to Helena.¹⁸

¹⁶ W. Lindgren, "The Igneous Geology of the Cordilleras and Its Problems," *Problems of American Geology* (1915), pp. 261-62.

¹⁷ R. T. Chamberlin, "The Building of the Colorado Rockies," *Jour. Geol.*, Vol. XXVII (1919), p. 148.

¹⁸ Clapp, *op. cit.*, p. 17.

This separating zone, or lineament, is in general synclinal; and from the Cœur d'Alene district eastward to Rock Creek it is an area of Belt sediments. East of Rock Creek, the rocks within this synclinal zone consist mostly of Paleozoic and Mesozoic sediments which are closely folded, broken by thrust faults, and intruded by small stocks.

The area which we are considering lies just south of, and partly within, this structural lineament; and in general its structures are more closely related to the complexly faulted and diversely arranged mountains than to the simple linear ranges of northwestern Montana. The Bitterroot Range, however, differs from the other ranges south of this lineament in having a linear, north-south trend, in being narrow in proportion to its length, and in standing boldly above the summits of the ranges to the east, north, and west.

The most striking structural features of the region are a series of nearly parallel thrust faults which trend in an east-southeast direction and which cut across older structures having a north-south trend (Fig. 3). Evidence for two episodes of folding and faulting is strong. The older north-south trending structures were probably produced during the earlier part of the Laramide deformation, or contemporaneous with the upthrust faulting and folding which produced the major linear structures north of the lineament.¹⁹ The later deformation produced the east-southeast trending structures of this region, particularly overthrust and underthrust faults.

FOLDING

In recognition of the two distinct episodes of deformation the folds of the region may be classified as those of the earlier group and those of the later group, corresponding with the earlier and later deformations.

Earlier folds.—The folds of the earlier deformation are large, simple in structure, and have a general north-south trend as a result of easterly directed stresses. Examples of these structures may be seen in both the Sapphire and Graves Creek ranges. Between the series of faults noted above and extending from the Clark Fork River to Cleveland Mountain in the Sapphire Range, a synclinal structure, traversed from east to west by the thrust faults, is readily observed.

¹⁹ *Ibid.*, p. 29.

The synclinal axis trends slightly east of north and plunges southward. Each successive fault to the south brings up older formations within the syncline and offsets these formations to the eastward, particularly on the western limb of the syncline. This offsetting is very noticeable when tracing the Hellgate formation from University Mountain, east of Missoula, across the Pattee Creek fault to Mitten Mountain, and southward across the Miller Creek fault to Miller Peak. Farther south the Hellgate quartzite again appears on Gilbert Creek, but the general plan of the structure is altered by the northward dipping Gilbert Creek wedge fault. South of the Eight Mile Creek fault the rocks, which consist of Appekunny quartzites and Grinnell argillites, lie nearly horizontal along the divide; and the synclinal structure is less conspicuous. In the Graves Creek Range, just north of Lolo Creek, the Newland limestone and Spokane contacts show a north-south trending anticline on the west, paralleled on the east by a similarly trending syncline. These structures are sheared off on the south by the Lolo Creek fault and on the north by the Blue Mountain fault.

Later folds.—These structures are very irregularly arranged, are of less magnitude than the earlier folds, are nearly closed or overturned to the north or northeast in many cases, and are highly sheared. They are closely associated with the east-west trending thrust faults and often are the results of dragging. In general, these folds trend in an east-west or northwest-southeast direction. The areas between the Eight Mile and Woodchuck Creek faults and also between the Davis and the Miller Creek faults offer excellent examples of these younger folds superimposed upon the older. In the latter area, the rocks occupy a part of the western flank of the older north-south trending syncline; and the general dip is to the southeast, as shown by the stratigraphic relations. However, the local strikes of the beds are often in a northwest-southeast direction, which also indicates the trend of the younger folding.

An overturned fold occurs just northeast of Burnt Fork Lake in the southeastern corner of the area. The overturn is toward the northeast, and the strike is nearly parallel to the underthrust faults. On the surface only the Newland limestone appears to be affected.

The limestone is highly metamorphosed, and along the under-stretched limb of the fold a basic dike intrudes the sheared limestone.

FAULTING

Faulting, because of the relative competency of the Belt series, is much more conspicuous in this region than folding, but, like the folding, it was produced during two periods of deformation. The first wave of deforming stresses produced thrusts along the Bitterroot Valley; the later gave rise to the more conspicuous east-west trending overthrusts and underthrusts.

In general the faults may be grouped into four separate types:

1. Overthrusts
 - a) Low angle
 - b) High angle
2. Wedge faults
3. Underthrusts
4. Normal faults

Overthrust faults.—Thrust faulting is the dominant type of rock failure in the region, and most conspicuous of the thrust faults are the nearly parallel overthrusts in the northern part of the area. Near the border of the Idaho batholith, west of the Bitterroot River, these overthrusts trend in nearly an east-west direction (Fig. 1). The faults farther north, however, have a trend nearly N. 50° W. The eastern extensions of all of the faults become obscured by river gravels. The thrust fault south of Lolo Creek and the Blue Mountain thrust bend southward up the Bitterroot Valley as they approach it; and the others, although obscured, may do likewise. Across the river to the east another series of faults, which may or may not be the same series of faults occurring west of the valley, has a general N. 70° E. strike and extends beyond the mapped area. The western extensions of these faults, in contrast to those west of the valley, appear to meet the river more directly, instead of curving to the southward. All of the overthrust faults are not only similar in trend, but they dip southward or southwestward; and the upthrow side is always on the south. As tentatively shown in Figure 1, the overthrust faults curve gradually southward and probably connect with similar north-south trending faults within the Philipsburg

Quadrangle. The throw of the faults ranges from 2,000 to over 10,000 feet.

Of the two series of faults, only the Clark Fork overthrust and the Davis Creek overthrust are of the low-angle type. The Clark Fork fault has a low dip of 10° – 25° and has thrust the Upper Belt rocks onto Paleozoic limestones. The horizontal displacement is nearly 5 miles. The Davis Creek fault, which probably is the northwesterly extension of the Philipsburg overthrust,²⁰ dips nearly due south in the area studied, at an angle of approximately 30° . The actual overthrust is about 2 miles. All the other overthrust faults of the series vary in dip from 50° to over 60° , and the amount of horizontal displacement is not definitely known. The Pattee Creek thrust appears to be the western extension of the Bearmouth thrust, which Pardee²¹ suggests may be an extension of the Philipsburg overthrust. If this is true, the Philipsburg thrust is probably not one of the older tectonic structures of the Laramide Revolution, as suggested by Emmons and Calkins,²² but is related in time and in genesis to the overthrusts described above.

Underthrust faults.—Whether a fault is to be considered an underthrust or an overthrust depends upon one's assumption as to the direction of the stresses that caused the breaking and whether the upthrow side is the passive or active block. All of the overthrust faults just described are assumed to have been caused by north- or northeastward-directed forces. This assumption is based on the fact that there is a lack of extreme brecciation and dynamo-metamorphism in the downthrow blocks and also because some of the later folds are overturned to the northeast. These overthrusts form the north and northeastern boundary of a synclinal wedge which, on the southwest, is bordered by the underthrusts described below.

From the Eight Mile Creek fault on the north, for a distance of 15 miles to the southward, the crest of the divide is composed of Grinnell and Appekunny quartzites. These formations are nearly horizontal with a gentle synclinal structure, and no conspicuous faulting was noticed. However, from Burnt Fork Creek southward another

²⁰ C. H. Clapp, personal communication.

²¹ Pardee, *op. cit.*, p. 170.

²² Emmons and Calkins, *op. cit.*, p. 146.

series of nearly parallel trending faults, which strikes about N. 50° W., is shown. The faults dip to the northeast, and the downthrow blocks are on the southwest. These faults are considered to be underthrusts, and since good evidence of underthrust faulting is present, the faults deserve individual description.

Dominic Butte underthrust.—This fault is probably one of the most interesting underthrusts described in the Rocky Mountains.²³ Its trace extends from the Rock Creek-Bitterroot divide southwestward for a distance of over 6 miles, beyond which it curves sharply to the east and then northeastward, forming a tongue-shaped loop. The width of the tongue near the crest of the divide is about 4 miles, but it narrows gradually southwestward to about 2 miles. A mass of brecciated Newland limestone, which is also highly metamorphosed, occurs on the west side of the tongue over an area more than $1\frac{1}{2}$ miles in width. As shown by the depth of Gold Creek Valley, the breccia is nearly 2,000 feet thick. Many blocks up to 6 feet in diameter consisting of scapolitized, brecciated limestone and quartzite are conspicuous along Burnt Fork and Gold creeks. Some quartzite pieces 10 inches in length were found in the large blocks of limestone. Also intruding the limestone breccia are small monzonitic stocks and basic dikes. The tongue which represents the upthrow side of the fault consists of Appekunny quartzite and Grinnell argillites. These older formations show but slight disturbances and directly overlie the younger brecciated Newland limestone. A fault dipping to the northeast and striking N. 40° W. cuts the tongue in two. This fault is probably the offset extension of the older Burnt Fork underthrust. Furthermore, extending along the Sapphire divide and near the northeast extension of the tongue, three limestone bands arcuate to the northeast. These bands of limestone are extremely shattered, and a small amount of basalt float was found near the contacts. Since no other limestone members are known to be older than the Appekunny quartzites, we must infer that the Newland limestone has been underthrust beneath the Appekunny quartzite as far as the divide and that these bands, in

²³ Credit for the correct mapping of this underthrust is given to Dr. C. H. Clapp; and since he plans to publish in detail his interpretation of the structures, only the major features are given here.

some manner, have been thrust up through the older quartzites. The amount of underthrust, as measured by the offsetting of the older Burnt Fork fault, is about $2\frac{1}{2}$ miles.

Burnt Fork underthrust.—The trace of this underthrust extends from the Ambrose Greek stock on the north for 7 miles southeastward to Burnt Fork Creek. Throughout much of this distance the fault is not readily seen but is well exposed just north of the creek. Upper Grinnell argillites on the west are in contact with the Appekunny quartzites on the east; and the displacement may not be over 4,000 feet, although, just north of the junction of Gold and Burnt Fork creeks, the highly brecciated Newland limestone comprises the downthrow block. The fault dips to the northeast at an angle of about 45° and is offset $2\frac{1}{2}$ miles to the southwest by the later Dominic Butte underthrust.

Gold Creek underthrust.—This underthrust strikes about N. 50° W. and has been traced from the divide northwest of Gold Creek southeastward, where it is also cut off by the Dominic Butte underthrust. The fault dips to the northeast. Like the Burnt Fork underthrust, the downthrow side is on the southwest, and Newland limestone is thrust beneath older Grinnell and Appekunny formations.

Stony Lake ramp.—This ramp comprises a narrow block of Newland limestone, averaging $\frac{3}{4}$ mile in width, which extends from Stony Lake northwestward to the Dominic Butte underthrust. The limestone has been badly shattered, and on either side it is faulted against Appekunny quartzites. The fault plane on the southwest is clearly exposed in a cirque on the divide and dips 50° to the southwest. The fault on the northeast side of the ramp dips to the northeast and probably is the continuation of the Burnt Fork underthrust.

Wedge faults.—For want of a better name the faults dipping to the north and occurring within the upthrow blocks of the major overthrusts are called "wedge faults." There are at least three of these faults forming narrow wedges, 1-4 miles in width and over 6 miles in length, in the hanging walls of the Miller and Davis Creek overthrusts. The stratigraphic throw of these wedge faults is in places over 3,000 feet, but as a rule it is less.

Woodchuck fault.—Although this fault has been traced north of Woodchuck Creek to the divide, the direction of dip could not be determined. The fault differs from the overthrusts as it arcuates to the southeast; but, like them, the upthrow side is on the south. Because of considerable distortion and brecciation along the fault, it is thought to be a thrust with the plane dipping to the southeast. As seen on the map, the fault encircles the block of undifferentiated Upper Belt rocks. These formations appear to be repeated by strike faults and also by east-west striking dip faults. Exposures are too poor to give a complete picture of the complex.

Normal faults.—Little evidence of normal faulting was found, except along the front of the Bitterroot Range. Although relaxational faults are to be expected in a region which has undergone such strong deformation as this, it is not likely that their displacement would be large enough to be detected, owing to the similarity and great thickness of the formations.

In 1904 Lindgren²⁴ believed that the east front of the Bitterroot Range is determined by an enormous flat fault of normal character. The dislocation was thought to involve a double movement, the hanging wall having gone downward while the foot wall moved upward. The writer's evidence for normal faulting does not agree entirely with that given by Lindgren, but the general conclusion is the same. The evidence is outlined below.

An unusually regular surface forms the eastern slope of the Bitterroot Mountain, slanting 15° – 35° toward the valley and extending the full length of the range. This surface is on both igneous and sedimentary gneiss, and generally conforms closely in strike and dip with the slipping planes.²⁵ Slickensides and striations on the surface give evidence of a movement usually parallel to the dip of the gneiss and the planes of movement. The strongest granulation and most closely massed slipping planes occur at the base of the range along the structural fronting plane. This plane extends upward to an elevation of over 8,000 feet in the area mapped. As stated by Lind-

²⁴ Lindgren, *op. cit.*, pp. 47–51.

²⁵ The displacement along the east front of the range has occurred along numerous slipping planes, with the development of a granulated gneissic zone nearly 3,000 feet in thickness.

gren, the maximum movement on the fault plane was 2 or 3 miles, and the throw between 4,000 and 6,000 feet. Evidences that the movement has been a double one are: (1) elevation of the Bitterroot Mountains 2,000 feet above the adjacent regions; (2) the depth of the valley fill, as shown by the well bore at Corvallis, where the gravels and clays extend downward at least 1,100 feet below the present valley bottom; and (3) the gradients of many of the streams, which become steeper as they near the valley.

The age of the fault is not definitely known, but that the faulting has continued to recent times is suggested by normal faulting which has occurred in the Curlew mines on the west side of the valley. Along this fault, gravels containing carbonized wood comprise the hanging wall, while the footwall is composed of pre-Cambrian quartzites and limestone. The fault dips to the east. Near the mine, actual faulting took place in 1898 along the contact of the sediments and gneiss.²⁶

PROBLEM OF THE BITTERROOT VALLEY

With the more detailed field work, not only is the normal faulting postulated by Lindgren verified but the fact is established that the valley has had a far more complex history than previously supposed.

Unfortunately, few bed rock exposures are found near the Bitterroot River between the mouth of Lolo Creek and the southern boundary of the map; therefore, little knowledge of the structure can be gained from an examination of the relations of the rocks at the foot of the Bitterroot Range and those exposed across the valley 9 miles to the east. However, from Eight Mile Creek northward the width of the valley narrows to only a mile at the town of Lolo. Here the structural relations are complicated by additional faulting. Helena limestone is exposed just west of the town of Lolo, but directly across the Bitterroot River are cliffs of distorted Newland limestone, and both formations have a general eastward dip. Consequently the younger Helena limestone appears to dip beneath the older Newland limestone; and, if we assume that no great folding has occurred within the distance across the river, it is very likely that Miller Peak argillites would dip beneath the Grinnell argillites

²⁶ Lindgren, *op. cit.*, p. 49.

or the Newland limestone as shown in cross section *DD'*, Figure 3. Two miles farther north this relation is fairly well shown, as eastward dipping Miller Peak argillites occur both east and west of the river, and just south of Miller Creek Grinnell argillites also have an eastward dip. The probable stratigraphic throw is therefore about 15,000 feet. From these facts it must be assumed that faulting has brought the older rocks on the east side of the river over the younger formations to the west, but the definite position of the fault is not known. The throw of this inferred fault, of course, cannot be exactly measured; but it appears to be of such magnitude that it is improbable that the fault would die out before reaching the front of the Bitterroot Range. This would give a faulted relation exactly opposite to that which would be produced if the Bitterroot Valley were entirely the result of displacement along a normal fault having a low dip to the east.

Evidence that this inferred Bitterroot thrust is probably older than the east-west trending series of overthrusts is seen in the north-south trending thrust fault east of the river. This fault dips about 60° to the west and is cut off on the north by the Pattee Creek thrust fault and on the south by the Miller Creek thrust. It is probable that this north-south trending fault forms a wedge in the hanging wall of the major Bitterroot thrust. Furthermore, considerable tributary faulting which shows underthrusting from the west or overthrust from the east occurs on the west side of the valley between Lolo and O'Brian Creek. Other evidence for thrust faulting preceding the normal faulting is found in faulted relations of the argillites and Newland limestone in the xenolith north of Mill Creek previously referred to.

Besides the foregoing evidence for a Bitterroot thrust, there has been some tearing along the front of the Bitterroot Range. Although the evidence is meager, this tearing is inferred because of (1) the probable dragging of the series of overthrust faults west of the valley from an east-west or south-east trend to a more southerly trend as they approach the valley, and (2) divergence in the dip of the gneissic structure from a normal eastward or northeastward direction to a southeastward direction. If the gneiss and schist bordering the batholith had resulted from only an upward movement of the magma, the foliation of the gneiss should parallel the

periphery of the intrusion. Therefore, on the northeast side of the batholith one should expect the dip of the gneiss to vary from north to nearly east, but it should in no case dip to the southeast. The fact that most of the dips taken show an east to southeast direction at the base of the range from Carlton Creek southward to Bear Creek, while higher on the slope the dip is more often in the expected east or northeast direction, suggests a northward shoving of the west side of the valley relative to the area east of the gneissic zone.

We may tentatively summarize the structural development of the Bitterroot Valley as follows:

1. Development of the large north-south trending Bitterroot thrust fault, dipping eastward and probably contemporaneous with the upthrust faults bounding the linear ranges in northwestern Montana.

2. Batholithic intrusion within the Bitterroot Range, with contemporaneous development of the series of overthrust faults and tear faulting along the older faulted and weakened zone, together with the dragging of the gneiss and bending of the faults to the south.

3. Normal faulting. This produced, at least in part, the slickensides and a granulation of the gneissic zone by sinking of the valley and uplift of the range along the zone which had been weakened previously by thrust faulting, intrusions, and tearing.

This complex history perhaps in part accounts for the considerable subsidence of the floor in a valley so narrow that its fill, ordinarily, would be easily supported by the strength of the earth's crust.

RELATIONS OF THE STRUCTURES TO THE INTRUSIONS

There are many reasons for believing that there is a close relationship of the structures of the second episode of deformation to the Idaho batholith, as well as to the minor injections; but some of the suggestions offered are only tentative. A brief summary of these suggested relations is given below.

1. The overthrust faults are arranged concentrically about the north and northeast margin of the Idaho batholith. They dip toward it and are overthrust from it.

2. The hypabyssal rocks are very abundantly injected along the fault planes and appear to have been injected during the actual period of faulting, as some are sheared while others are little disturbed or unaffected. These dike rocks associated with the faulting are also similar in composition to the facies of the major batholith. They often are aschistic and vary in composition from tonalites to granites. However, basic monzo-gabbros also occur along the shear zones.

3. There is a relatively rapid increase in the complexity of the structures as the intrusion is approached. It therefore appears that the batholith is at the focal point from whence the forces have been directed.

4. The zone of younger gneisses and schists occupies in this region an area of nearly 150 square miles; and there is a greater development of the schistosity in the extreme northern part of the Bitterroot Range than farther south along the eastern side, which possibly indicates greater mushrooming of the batholith to the north.

5. At the base of the Bitterroot Range paralleling the valley the dip of the older gneiss seems to have been dragged slightly from its normal position. Also, the overthrust faults north of the range which can be traced nearest the river bend southward up the valley, and the others may do likewise. These factors may indicate a relatively greater northward movement of the intruded rocks west of the river than east of it.

Unfortunately, time was not available for any detailed work with the methods used by Cloos. The area, however, offers adequate exposures for very detailed examinations.

If we prefer to accept the view that the structures described above were produced by other forces than those transmitted by the batholith, areas farther from the batholith should give some record of such forces. On the other hand, if we accept the evidence suggesting relationship to the batholithic emplacement, it follows that the age of the intrusion must be late Cretaceous or early Eocene, as the overthrust faulting has been shown to cut the older structures produced in the earlier stages of the Laramide Revolution. Furthermore, since it is very probable that the Bearmouth fault and Philipsburg fault are related in age, and as these are tentatively correlated

in age and genesis with the overthrusts here discussed,²⁷ we have additional evidence for a late Cretaceous or early Eocene age of the latter. If the batholith is older than the thrust faulting adjacent to it on the north, some shearing within the massive granite should be present and the trend of the shear planes should correspond to the trend of the faults. Some shearing in the schlieren gneiss was noted; but these shear planes have a north-south strike, which is nearly at right angles to the trend of the overthrusts. In any case, the shearing is not conspicuous and probably only indicates that the area was still under the influence of easterly directed stresses after parts of the magma had solidified, or else the renewal of compressive stresses at a later time. On the other hand, east-west perpendicular jointing across the gneiss is abundant and would indicate, according to Grout,²⁸ tension or a direction of least pressure; hence a direction of motion at right angles to the joints.

Cloos's methods of investigating granite tectonics are based primarily on the assumption that magmas intrude under directed stresses. The shapes of most of the larger intrusives in folded mountain ranges seem to justify this assumption because of their elongation parallel with the folds and normal to the direction of the active forces. One would, therefore, expect a magma in process of emplacement to be somewhat analogous to a viscous solution being compressed between vise-like jaws in the earth's crust. As the western jaw moved inward, the other jaw would remain passive or move less rapidly eastward. Thus, in a region under eastwardly directed stresses, the magma would rise²⁹ until a definite zone in the upper crust was reached where horizontal thrusting aside of the country rocks would be easier than for the magma to rise higher. With tangential diastrophic forces one would expect the batholith in this region to thrust farther to the east than to the west, even if the pressures exerted by the upper part of the magma were only hydrostatic.

²⁷ C. H. Clapp, personal communication.

²⁸ F. F. Grout, *Petrography and Petrology* (New York: McGraw-Hill, 1932), p. 199.

²⁹ It is not inferred that the rise of magma was due only to horizontal pressure, as factors suggested by others for the ascension of magma are too numerous to be stated here.

As previously stated, there is evidence that considerable tearing has occurred along the Bitterroot Valley, with the probability of a relatively greater northward movement of the western side. Reason for the necessary easy horizontal relief to the north possibly may be found in the relations of the intrusion to the older Bitterroot thrust fault. This fault dips to the east or away from the batholith which has intruded on the west. The initial condition would therefore give rise to underthrusting, instead of overthrusting, if stresses were directed from the batholith. The underthrust faults in the Sapphire Range have been described. Since underthrusting is thought to be normally accomplished less easily than overthrusting,³⁰ although some geologists would disagree, the resultant of the radially directed stresses from the northeast portion of the batholith would be rotated to a more northerly direction, and tearing would develop along the weakened zone of the valley.

Another factor which may have aided northward thrusting of the confining rocks of the batholith is the trend of the synclinal lineament which separates the linear ranges on the north from the more complex ranges to the south. This lineament nearly parallels the northern boundary of the batholith. It probably had its origin in pre-Cambrian times³¹ and apparently was a downwarp through much of Paleozoic and Mesozoic time. In other words, it was a zone of weakness; and the initial dip of the formations would facilitate overthrusting to the north or normal to the axis of the syncline.

Further evidence that the area south of this downwarped zone has probably been the active region since the development of the earlier Laramide structures is seen in the trend lines of the upthrust faults of the northern linear ranges, as shown in Figure 1. These faults, such as the Mission fault, dip to the northeast, normally arcuate to the southwest, and are the older ones of the area. Their normal trend is about N. 30° W.; but as they approach the southern area, which is highly intruded by igneous rocks, they swing rapidly eastward; and the Mission fault, which is the nearest of these major upthrusts, to the batholithic masses on the southwest, actually arcu-

³⁰ G. R. Mansfield, "Structure of the Rocky Mountains in Idaho and Montana," *Geol. Soc. Amer. Bull.* 34 (1923), p. 272.

³¹ Clapp, *op. cit.*, p. 29.

ates to the northeast. It seems very probable that this change of its trend, with a bowing-out to the northeast and essential parallelism to the later overthrust faults, may have been effected by the same stresses that produced the overthrust faults which are related to the intrusions.

The Osburn fault³² also indicates a shift of nearly 12 miles parallel to the zone separating the linear ranges on the north from the diversely arranged group of mountains on the south. The fault, like the overthrusts north and east of the batholith, was developed later than the north-south trending structures. Unfortunately, no evidence has been found as to whether the northern area or the hanging wall on the south was the active one; but since the fault nearly parallels the Idaho batholith to the south and is clearly related to igneous intrusions, it is very probable that it is closely related in time and genesis to the overthrusts of our area, and the 12 miles of shifting along it may, in part, be the result of magmatic forces.

The writer, however, is well aware of the fact that the total displacement along these thrust faults is large and that normally the emplacement of even some of the largest igneous bodies seems to have taken place without excessive deformation of the surrounding country rocks. But even so, the most conservative student will probably find it difficult to attribute the strikingly concentric arrangement of structure around this igneous body to forces other than those of the intrusion itself. In this respect the Idaho batholith appears to be in harmony with the views of Professor Chamberlin.³³

SEQUENCE OF EVENTS

In conclusion, the geologic events since the earlier episode of the Laramide Revolution appear to have been as follows:

1. Uplift, development of the northerly trending folds and the Bitterroot thrust fault.

2. Intrusion of the Bitterroot Range by a portion of the Idaho batholith and development of the later structures. The under-

³² J. B. Umpleby, "The Osburn Fault, Idaho," *Jour. Geol.*, Vol. XXXII (1924), pp. 601-14.

³³ R. T. Chamberlin and T. A. Link, "The Theory of Laterally Spreading Batholiths," *Jour. Geol.*, Vol. XXXV (1927), pp. 319-52.

thrusts probably preceded the series of overthrusts (and the Dominic Butte underthrust is younger than the other underthrusts).

3. Intrusion of smaller bodies of aschistic and diaschistic hypabyssals. This gave rise in an early stage to thrust faulting, but the injections continued later than the movement along the shear planes which they intrude. The larger stocks appear to be somewhat younger than the thrust faulting.

4. Development of an old erosion surface across the later intrusives and deformed sediments.

5. Extrusions of andesite lavas, followed by a regional uplift and the development of the Tertiary lake deposits.

6. The rise of the Bitterroot Range, which appears to have continued long after the adjacent ranges became passive. The floor of the valley subsided, and has continued to do so with slipping along the bold fronting plane to the present day.

7. In Pleistocene times the higher Bitterroot Range was more heavily glaciated than the lower adjacent ranges. Melting of the ice gave rise to Lake Missoula. As shown by the well-preserved terraces on the mountain slopes, the lake disappeared very recently.

